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Viavattene, Christophe ORCID logoORCID: <https://orcid.org/0000-0002-4358-5411>, Ellis, John Bryan, Revitt, D. Mike, Sieker, Heiko and Peters, Christian (2010) The application of a GIS-based BMP selection tool for the evaluation of hydrologic performance and storm flow reduction. In: NovaTech 2010, 7th International Conference on 'Sustainable techniques and strategies in Urban Water Management', 27 June - 1 July 2010, Lyon, France. . [Conference or Workshop Item]

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The application of a GIS-based BMP selection tool for the evaluation of hydrologic performance and storm flow reduction

Utilisation d'un outil d'aide au choix des techniques de gestion des eaux pluviales basé sur un SIG pour évaluer la performance hydrologique et la réduction des ruissellements

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RÉSUMÉ

Dans le cadre du projet Européen SWITCH, un outil SIG a été développé afin de permettre à divers acteurs d'identifier les bonnes pratiques de gestion des eaux urbaines. L'objectif est d'assurer une meilleure gestion des eaux de ruissellement et une réduction de l'émission de polluants vers les eaux de surface. Le couplage de l'outil avec un modèle hydrologique (STORM) permet de mesurer l'impact des techniques alternatives sélectionnées sur les débits dans les réseaux de collecte d'eau de ruissellement. L'exemple d'un secteur en développement de 4.5 ha en centre ville, soumis à d'intenses précipitations illustre les possibilités offertes par un tel couplage. Les techniques testées sont les toits verts et les pavés poreux. Les résultats montrent un potentiel de réduction compris entre 23 et 26% et entre 22 et 28% pour ces deux techniques respectives; ce potentiel estimé par heure varie en fonction des précipitations. L'utilisation conjointe des deux techniques peut ainsi résorber les surcharges sur le réseau de collecte. Elle réduit aussi la variabilité à court-terme de l'écoulement dû aux variations de précipitations permettant ainsi aux gestionnaires de planifier plus précisément la capacité de leurs réseaux de collecte.

ABSTRACT

A GIS-based BMP tool has been developed within the EU-funded SWITCH project to enable stakeholders to identify appropriate BMPs and their locations to facilitate the control of urban runoff and to reduce the pollutant loads discharged to receiving waters. The attenuation impact of the installed BMPs on separate sewer flows has been predicted by linking this tool to a hydraulic model (STORM). The capability of this combined tool is illustrated using a 4.5 ha section of a city centre development site subjected to measured rainfall data for an extreme storm event. Green roofs and porous paving are used as illustrative examples of BMPs and are shown to have the potential to remove 23-26% and 22-28%, respectively of hourly based flows depending in the incident rainfall volumes. When used in combination, these BMPs have the potential to alleviate exceedance flows in the receiving pipe system. The installation of BMPs is also demonstrated to reduce the short term flow variability caused by rainfall fluctuations and hence to enable planners to more accurately design sewer systems with the required capacity.

KEYWORDS

Urban runoff, BMP selection. BMP performance, GIS, storm flow reduction

1 INTRODUCTION

A number of decision-support systems have been developed to assist stakeholders in the selection and implementation of appropriate best management practice (BMP) stormwater control facilities. Given the range and flexibility of available BMP options for stormwater drainage infrastructure, there is clear scope for the application of robust modelling approaches to support the selection and evaluation of viable BMP (or other Low Impact Development; LID) options. Such approaches help stakeholders in their decisions not only with respect to the selection of appropriate BMPs, but also their strategic placement within an urban site or sub-catchment, in terms of optimum performance and cost-effectiveness to address concerns on environmental quality and impairment. Most approaches utilise a matrix structure based on some form of “bottom-line” criteria where BMP performance is scored against technical, environmental, economic, social, legal and/or other indicators (Scholz, 2006; Lai *et al.*, 2006; Ellis *et al.*, 2008).

To provide maximum stakeholder decision-support, these modelling tools should be seamlessly integrated within a GIS-based interface and driven by recognised process-based hydrological, hydraulic and pollution simulation models. There have been a number of recent BMP decision-support systems which offer such coupled GIS/hydraulic and quality modelling approaches (Makropoulos *et al.*, 2001; Lai *et al.*, 2007; Viavattene *et al.*, 2008). The “front-end” tool within these GIS-based decision-support approaches usually provides assessment criteria to help develop, evaluate and select BMP options based on site properties and effectiveness, cost and other legal, social and amenity factors. This approach provides a tool for a more objective analysis of management alternatives against multiple interacting and competing factors. The “back-end” tool of both the US EPA (Lai *et al.*, 2007) and the EU 6th Framework SWITCH (Viavattene *et al.*, 2008) approaches provides a placement tool for the strategic location of BMP facilities with a practical and informative assessment of those stormwater control options in terms of their water quantity and quality effectiveness. These GIS-based models are intended to support a range of local authority/municipal, federal/state regulatory agencies, drainage engineers/consultants and other interested stakeholders in the development and evaluation of stormwater drainage infrastructure contained within stormwater management plans. However, the detail incorporated in these GIS-based approaches is such that users must be expected to have at least a basic working knowledge of surface water drainage and BMP modelling processes in order to appreciate and utilise their full capabilities.

The large majority of management decision approaches and systems for BMP implementation are based on performance criteria related to maintaining the pre-development runoff volume utilising compliance standards requiring peak flow attenuation and storage, with designs frequently related to the capture of 80%-90% of the annual storm events; this latter compliance strategy being aimed at both quantity and quality control. However, there have been a number of studies which have recently queried the basis for this BMP drainage design philosophy and have advocated total runoff volume as the prime currency for BMP evaluation (Hirschman *et al.*, 2008; EPA, 2008; Reese, 2009). This assertion contends that source capture and diversion of total runoff volumes will achieve more sustainable management outcomes than approaches focussing on other variables such as peak flow attenuation, flow velocities or pollutant Event Mean Concentrations (EMCs). It is argued that achieving total runoff reduction is a first and necessary step for urban drainage management and receiving water compliance.

This paper describes the GIS-based BMP tool developed within the EU SWITCH project and demonstrates the capabilities of the modelling functions in respect of the performance-effectiveness of selected BMP options and describes the use of the BMP tool in respect of evaluating total runoff reduction as a key BMP performance standard. The BMP modelling tool and BMP performance evaluation is developed in respect of a proposed inner urban regeneration development area within the city of Birmingham, UK.

2 METHODOLOGY AND MODEL STRUCTURE

Details of the GIS-based BMP tool methodology and structure have been given elsewhere (Viavattene *et al.*, 2008), with a formal user guide published (Viavattene, 2009) as a public domain document within the SWITCH project (www.switchurbanwater.eu). The front-end decision support tool comprises the integration of a process-based BMP pollutant removal performance assessment with site characteristics and a triple-bottom line multi-criteria analysis for the identification of appropriate BMPs.

These components are integrated under a common ArcGIS platform with the incorporated Microsoft Access database allowing the ArcGIS interface, BMP pollutant and site modules to interact and exchange data. In addition to the linkage with external hydrologic/hydraulic models such as STORM, the BMP tool includes internal, stand-alone modules that can be used individually or in combination for multi-criteria analysis (MCA), BMP pollutant process simulation or as a BMP data/information catalogue. There are three types of interactive map functionality of which the “ADD BMP Tool” option allows the user to use the mouse to add a BMP to a dedicated urban landuse layer which geo-references existing and new BMPs for further modelling analysis.

The design and structure of the major system component relationships within the BMP decision tool are shown in Figure 1. The use of discrete components developed as individual functional models in a user-friendly form provides a considerable flexibility in the development and maintenance of the

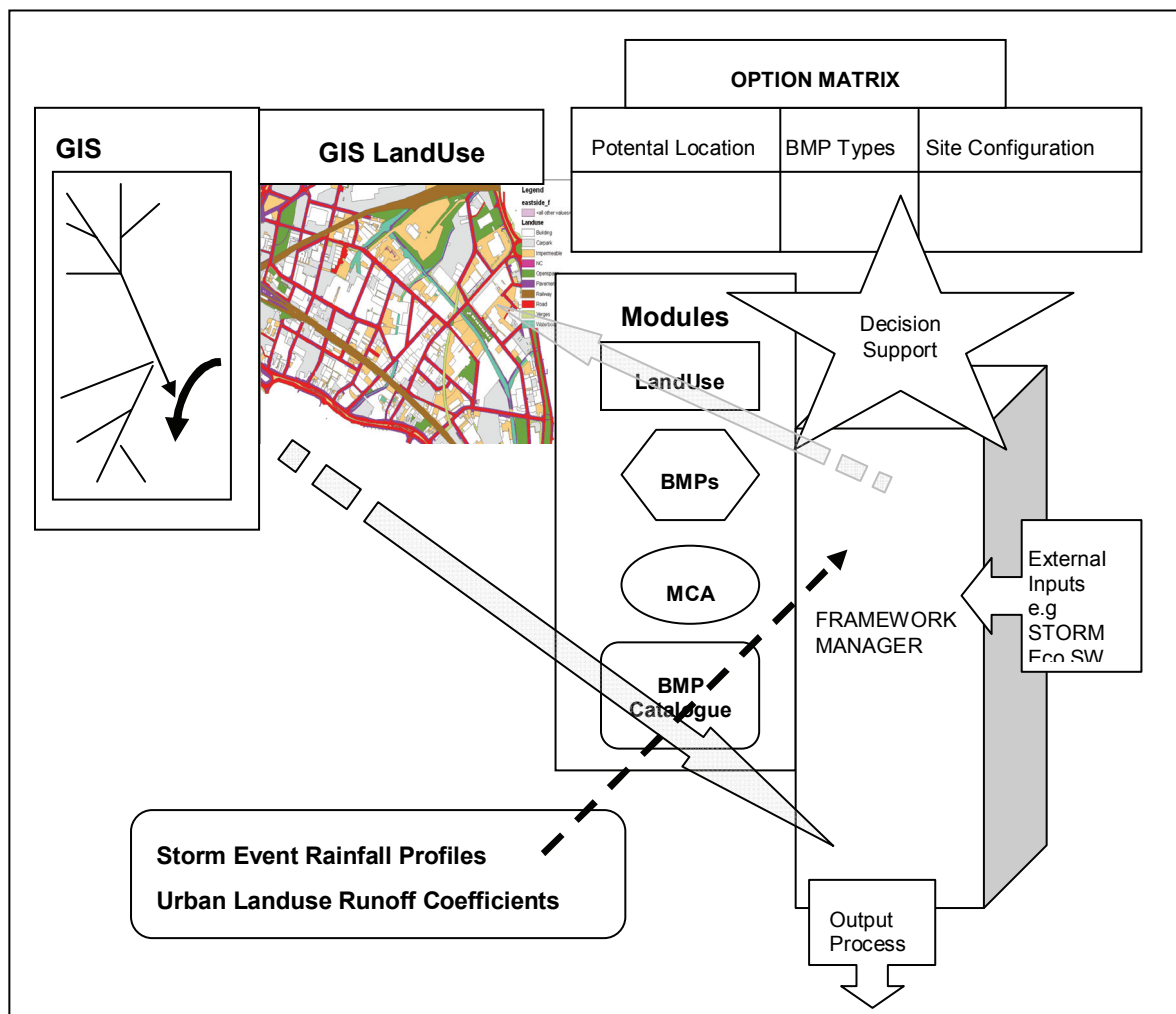


Figure 1. Conceptual diagram of the BMP tool structure

modelling structure. The main user GIS interface provides the flexibility to support the selection and spatial placement of BMPs and the evaluation of the sewer network from individual link up to full sub-catchment level. The MCA module allows the user to select objectives such as to minimise the total cost for a specified BMP quality effectiveness and/or set water quality control targets and provides a matrix-based analysis for the evaluation of a full range of criteria and indicators through a benchmarking technique. Unlike the US EPA SUSTAIN model of Lai *et al* (2007) however, the current BMP Tool cannot evaluate or compare costs of alternative BMP implementation plans. Nevertheless, the structure of the modelling framework does allow the input of an external model such as the lifecycle costing tool Eco.SWM developed by IPS mbH within the SWITCH project (Seiker, 2007) to enable such costing assessment to be undertaken

3 MODEL APPLICATION

The BMP modelling tool is being applied to the 170 ha Eastside urban development of the city of Birmingham; the second largest city in the UK. This inner urban development area lies immediately to the south of the city centre and has been undergoing major regeneration over the last five years. It is planned that the area should become a new learning, technology and heritage quarter for the city providing a range of learning and employment opportunities (Birmingham City Council, 2008). There is a common will shared by all of the stakeholders in the Birmingham SWITCH Learning Alliance to incorporate sustainable development into the regeneration programme. From a water perspective, the city has to deal with major issues on both water quantity and quality. In particular, the area is subject to rising water tables resulting from a decline in the area's industry and the greater part of the run-off from Birmingham city centre flows towards the River Rea (Eastside Sustainable Vision, 2002). Severn Trent Water Ltd is facing increasing sewer network surcharging problems within its region, much of which is related to pluvial surface water flooding. For example, Foster *et al* (2007) have shown that a large component of the Eastside sewerage network is susceptible to surcharging during a 5 year 60 minute design rainfall event. As a contribution to addressing these issues, the use of BMPs within Eastside's ongoing and future regeneration projects is being actively considered, and base data has been collected to enable a preliminary application and testing of the GIS-based BMP Tool.

The topographic layer of Master Map® data has provided initial information on urban landuse types as indicated in Figure 2 for a 4.5 ha section of the development site. Further refinement to discriminate between specific land use areas e.g. car parks, "other" impermeable hard standing areas, open spaces, derelict land and verges has been achieved using images obtained from Google Earth 2007 and by referring to data obtained from ©2008 Infoterra Ltd & Bluesky. Soil data were obtained from the relevant Ordnance Survey of Great Britain geological map and from the SOILSCAPE™ Website

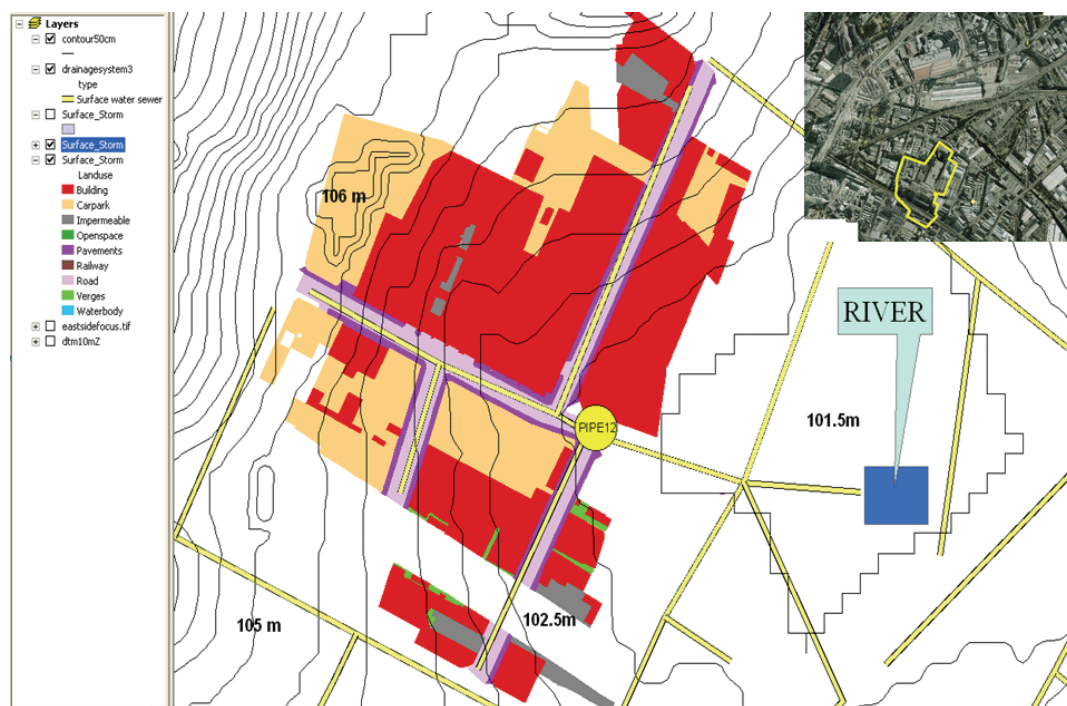


Figure 2. LIDAR topographic image for a 4.5 ha section of the Birmingham Eastside development area (Cranfield University, 2008)

Surface gradients have been calculated using the Digital Terrain Model (DTM) available through the Ordnance Survey/EDINA supply service. The current existence of flat roofs presented the most problematic aspect, and initial allocations were achieved by analysing remote sensing data available within Google Earth and later verified and calibrated by ground survey. Detailed groundwater data have been obtained from Birmingham University and information on groundwater quality is also available from the same source but has not been utilised in the modelling studies to date. More detailed LiDAR topographic imagery is also available from the Environment Agency which enables a

vertical contouring resolution of ± 50 cm as seen from Figure 2 which represents a 5 ha section of the development area outlined in the Google Earth inset diagram. Figure 2 shows the relatively steep slopes lying to the north west of the development area which rapidly drain the separately sewered surface water down towards the receiving watercourse of the River Rea. The flatter ground of the development area itself is therefore subject to considerable flash flooding during extreme event conditions when the surface water outfalls to the Rea channel become blocked by rising fluvial flows in the main receiving water channel. There is therefore considerable incentive to seek source control solutions to divert storm flows from the stormwater sewer network. The proposals for extensive flat roofing, car parking and other paved surfacing within the regeneration programme offer scope for a variety of BMP options including green roofs, porous paving and small-scale biofiltration systems, particularly for roof disconnection and road runoff.

Rainfall data from an extreme event which occurred on the 13 -14 June 2007 have been used with the STORM model to derive surface water flows within the 4.5 ha section of the development area shown in Figure 2 and outlined in the inset diagram. This >1: 80 storm event generated a total of 35 mm over a 10 hour period with a maximum intensity of 0.6 mm/min and caused widespread pluvial flooding in the area from a combination of sewer surcharging, overland flow and groundwater flooding. It is appreciated that a continuous time series simulation rather than single-event modelling is probably required for fully accurate results, as what happens between storm events is just as important as what happens during a specific extreme design event. However, for this preliminary model testing, it was decided to use a single design storm with a “blanket” rainfall distribution applied across the experimental catchment. The nodal surface water pipe (PIPE12) shown in Figure 2 receives the flows from three upstream sewered sub-catchments as indicated in Figure 3 using the STORM model. It is these three minor branch sewers which comprise the 4.5 ha experimental catchment, that have been used in the preliminary testing of the model and on which the results of the BMP Tool are discussed in this paper.

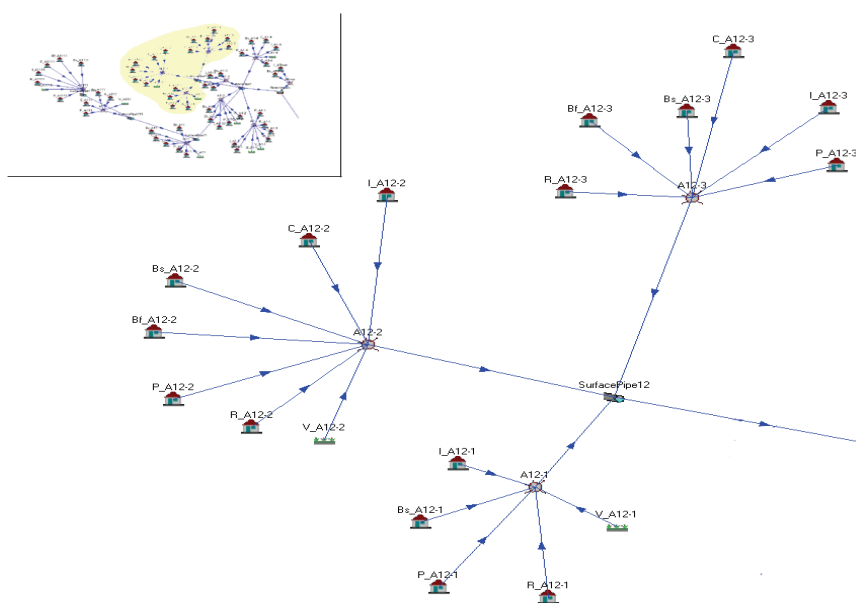


Figure 3. The STORM modelled sewered sub-catchments in Eastside

4 RESULTS

The simulation outcome predicted by the STORM model for the PIPE12 nodal link to the three sewered sub-catchments in the experimental 4.5 ha Eastside development is shown in Figure 4. A very rapid response in the pipe flows to the rainfall distribution is predicted with very short lag

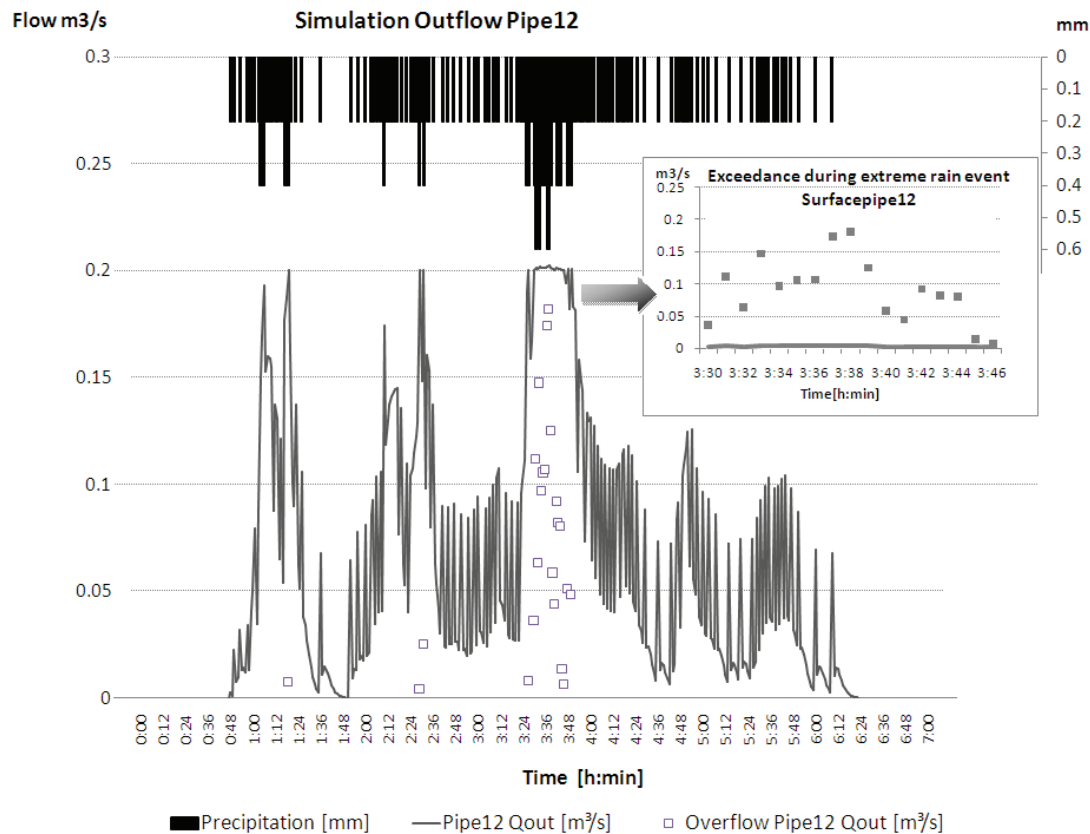


Figure 4. Predicted flow distribution and exceedance overflows for an extreme storm event

times, frequently less than 3 minutes. The hydraulic capacity of this separately sewered pipe system is exceeded by flows greater than $0.2 \text{ m}^3/\text{s}$ and thus surcharged overflows from the PIPE12 manhole occurred frequently during this extreme event as shown in the inset diagram to Figure 4, which illustrates the values of the exceedance flows at one minute intervals between 03.30 and 03.45 hours. The rapid response and exceedance overflow of small diameter surface water drainage systems during extreme events is now recognised as being a major issue for urban pluvial flooding (Pitt, 2008; Gill, 2008). The problem can only be successfully resolved by the introduction of management strategies which actively utilise source controls.

The developed SWITCH BMP Tool allows the user to identify and add a particular type of BMP to a GIS-based urban landuse distribution. The tool interacts through the mouse cursor symbol to select an appropriate BMP location. As the cursor moves across the screen, the cursor image changes automatically in relation to whether the site area is suitable or not for the particular BMP being considered (Viavattene, 2009). Figure 5 shows locations within the Eastside experimental sub-catchment where the BMP Tool considers that both green roofs and porous paving are possible drainage solutions, covering 40% (1.8 ha) and 30% (1.35 ha) of the total 4.5 ha surface area respectively. The STORM model was then re-run with these BMPs in place with the simulation outcome shown in Figure 6. The sewer overflow times remain much the same as previously predicted, but the severity and incidence of surcharging is reduced. It is also clear that a considerable 'damping down' of the flow variability in response to the rainfall fluctuations is predicted with the BMPs installed. The patterns of runoff volume reductions during the storm event for the two BMP forms are shown separately in Figure 7, which illustrates the performance effectiveness of both source control facilities.

It is clear that GIS-based platforms can help identify pluvial flood risks resulting from complex urban surface-sewer interactions as well as supporting stakeholder evaluation of the performance effectiveness of differing BMP controls. Such modelling tools can facilitate the design, selection and location of BMP source controls to make "space for flood water" and to ensure minimum adverse effects on proposed as well as existing development.

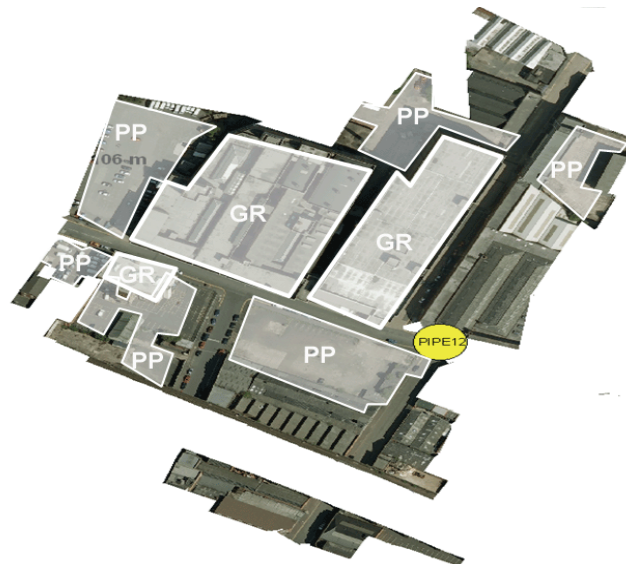


Figure 5. Identified green roof (GR) and porous paving (PP) placement in the studied catchment

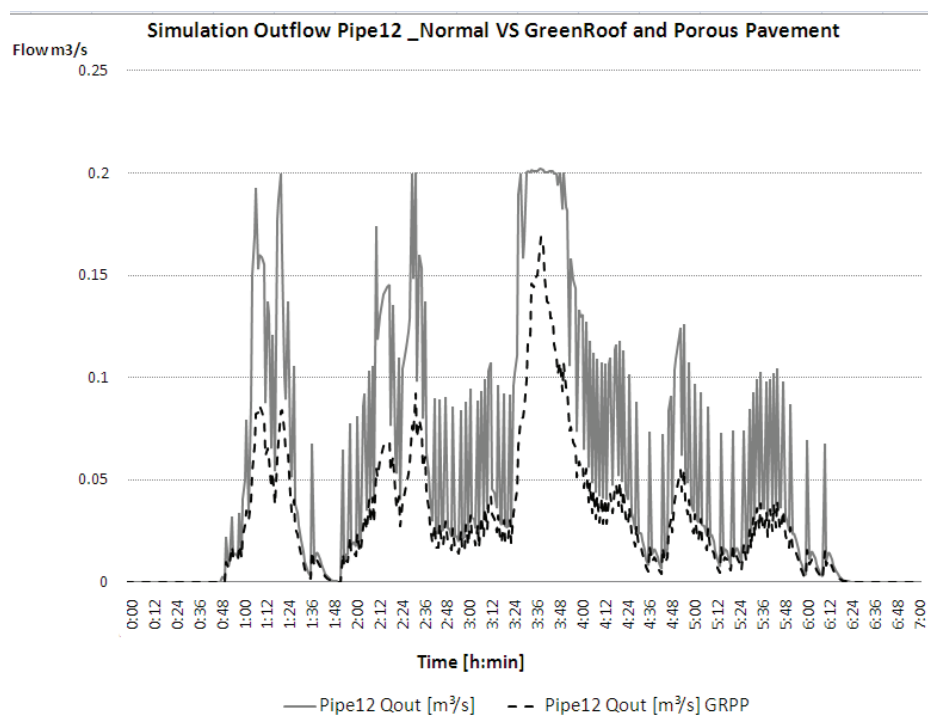


Figure 6. Comparison between predicted flow distributions with and without BMPs installed

5 RUNOFF REDUCTION

The storage and treatment of urban surface water discharges are necessarily less effective and generally more costly than runoff removal at source. In addition, consideration of flow rates/volumes over time, rather than peak flows *per se*, appear to be more beneficial in terms of reducing downstream erosion (Hirschman et al., 2008; Reese, 2009). Source runoff reduction involves a mix of green roofs, rooftop disconnection, rain gardens and other bioretention facilities for highway/car park runoff, grass channels and small-scale infiltration BMP controls. Only after these first set of practices have been introduced should other BMP forms such as ponds and wetlands be considered. Table 1, based on literature values for over 150 individual storm events covering a period of nearly 10 years,

indicates the range of total runoff reductions recorded (measured as the difference between inflow and outflow). Whilst there is a wide performance range it can be seen that conveyance and storage controls clearly contribute very little to overall reductions in runoff volumes.

BMP	RUNOFF REDUCTION (%)
Green roof	45 – 60
Rooftop disconnection	25 – 50
Porous Paving	45 – 75
Grass channel	10 -20
Bioretention (including raingardens)	40 -80
Infiltration	50 – 90
Ponds/Wetlands	0 - 10

Table1. Reported BMP total runoff volume reductions
(Table compiled from: Strecker *et al.*, 1999; Hirschman *et al.*, 2008; www.bmpdatabase.org)

Biofiltration forms (e.g swales, filter/buffer strips, raingardens etc.) according to Strecker *et al* (1999), generate an average of 20% less runoff volumes on a storm-to-storm basis than ponds/wetlands and are consistently lower for the large majority of storm events. If small storm events are removed from the record, Strecker *et al* (1999) estimate that both biofiltration and dry detention basins contribute significantly to volume reductions (by 30% - 40%), although they are not normally designed for this purpose.

Runoff capture and storage still leaves the question of how the volume is “lost” in the interim period between storm events and some proportion of “detained” pollutants are likely to overflow (and also perhaps be toxically mobilised) in subsequent flow events. The focus in regulatory compliance on peak flow attenuation and/or pollutant EMC non-exceedance can be regarded as being misplaced if it is accepted that the root cause of receiving waterbody impairment is essentially the increase in volumes brought about by impermeable urban development. If this argument is accepted, it may well be that a focus on reducing the total runoff volume could offer a more direct means of achieving compliance standards and this precept has been acknowledged in the recent US National Research Council (2008) stormwater report. Such a focus on volume reduction might then pull other flow and water quality based variables into line. Such runoff volume reduction approaches are already being practiced in California, Vermont and Washington states where the prevailing standard is flow duration based, with the express objective of reducing and controlling in-stream erosion and siltation. The US EPA Combined Sewer Overflow (CSO) policy has a similar presumptive volume-elimination option.

Reduction in total runoff volume will have consonant reduction in total pollutant loads. A source reduction in volume has a much greater effect on loads than direct capture, storage and treatment of runoff volume. The true performance of a BMP only becomes apparent when the impact of volume reduction is factored into the calculation of total pollutant loadings.

The runoff reduction performance of the simulated green roof and porous paving BMPs inserted into the Birmingham Eastside development area indicate that substantial reductions in total runoff volumes can be achieved. However, the average 22% - 28% reductions for the 4.5 ha site generated by the simulation modelling shown in Table 2 appear to be only some 50% or so of the minimum figures

Time Period	Precipitation (mm)	FLOW (m ³)			FLOW REDUCTION (%)	
		Normal	Green Roof	Porous Pavement	Green Roof	Porous Pavement
1am-2am	5.6	230	169	174	26%	25%
2am-3am	7	304	227	220	25%	28%
3am-4am	13	568	425	410	25%	28%
4am-5am	5	228	171	166	25%	27%
6am-7am	3.2	143	107	104	25%	27%
7am-8am	0.2	13	10	10	23%	22%

Table 2. Birmingham Eastside BMP runoff volume reductions

reported in the literature (Table 1). However, the data in Table 2 gives flow reductions for the green roof/porous paving 3.2 ha scenario set within the context of the whole 4.5 ha catchment. Therefore the reductions shown in Table 2 take into account the flow reduction of both the BMP forms and those of their representative surface areas. If surface area adjustments are factored in, the true BMP flow reductions range between 57% - 65% for the green roofs and 73% - 93% for the porous paving. However, it would not be wise to rely on the outcomes of any individual single event to characterise the general long term cumulative performance behaviour of these BMP forms. There is a need to consider the full distribution and sequence of flows within the context of the overall flow regime and as rainfall depths/intensities increase, the design concern will shift from source infiltration and volume reductions to site flood reduction and wider-scale pluvial/fluvial catchment management. As indicated in Figure 7 the timing and patterns of volume reduction for both BMP forms are very similar, with both BMPs showing a rapid response to the variability in rainfall inputs over time. The porous paving does exhibit a much greater variability than the green roof particularly during the earlier part of the storm event which reflects the “pump” action of the infiltrative mechanism associated with the porous surfacing and rapid temporary blocking of the underlying sub-base horizons. The green roof by comparison is able to soak-up a larger proportion of the incident rainfall. Both BMPs become more stable to rainfall fluctuations after the peak rainfall intensity, probably as a result of saturation of the BMP storage sites

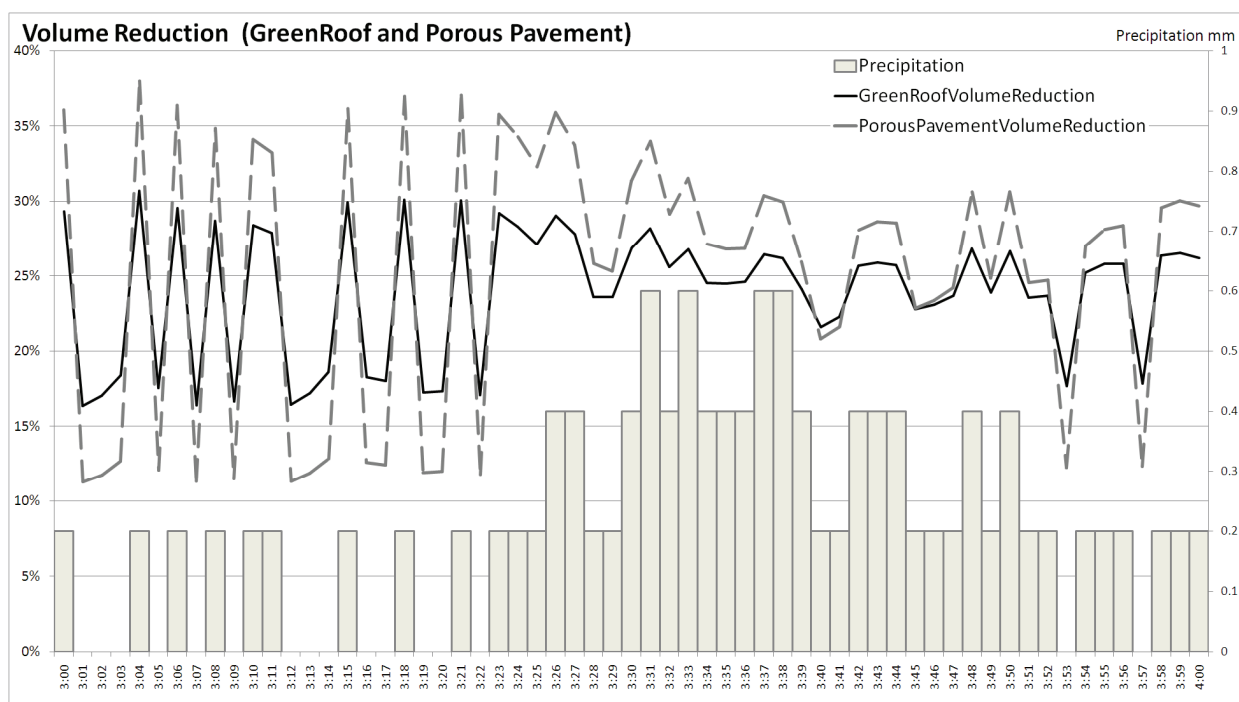


Figure 7. Temporal variations in runoff volume reduction in relation to the rainfall pattern

Effective hydrologic mitigation for urban development cannot just aim to maintain pre-development peak flows and individual BMP controls on stormwater discharges are frequently inadequate in themselves as the sole solution to runoff impairment in urban catchments, especially for extreme event conditions. The use of retrofitted serial bioretention cells together with (limited) rooftop disconnection have been successful in reducing total runoff volumes in Seattle (Horner and Chapman, 2007). Source runoff volume reductions combined with site and sub-catchment green infrastructure development are much more likely to achieve both quantity and quality control to cover the full spectrum of storm events (Hirschman *et al.*, 2008; Ellis, 2009).

6 CONCLUSIONS

The results presented in this paper clearly demonstrate that GIS-based platforms can assist in providing a better understanding of how rainfall-urban surface-sewer interactions can lead to surface flooding. In addition, such platforms can inform stakeholders of the benefits which can be achieved by the appropriate location of selected BMPs. Therefore these modelling tools can facilitate the best use

of BMPs to counteract pluvial flood risks and to ensure minimum adverse effects on proposed as well as existing development. Where exceedance surface water flows are generated during extreme storm events it is important to be able to predict surface flowpaths, flood depths and velocities and in order to facilitate this, innovative coupled 1D/2D modelling approaches are currently being incorporated into the tool. It is envisaged that the extended tool will make an important contribution to those stakeholders whose aim is the achievement of sustainable urban drainage management through the control of surface flooding due to extreme rainfall events.

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